

Out-of-Band Radiation from Large Antenna Arrays

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Abstract

Co-existing wireless systems that share a common spectrum need to mitigate out-of-band (OOB) radiation to avoid excessive interference. In legacy SISO transmitters and small MIMO arrays, OOB radiation is well understood and is commonly handled by digital compensation techniques. In large arrays, however, new phenomena and hardware limitations have to be considered: First, signals can be radiated directionally, which might focus the OOB radiation. Second, low-complexity hardware with poor linearity has to be used for cost reasons, which increases the relative amount of OOB radiation. Given that massive MIMO and millimeter wave communication rely on base stations with a huge number of antennas, the spatial behavior of OOB radiation from large arrays will have significant implications for future hardware requirements. We show that, if the OOB radiation is beamformed, its array gain is never larger than that of the in-band signal. In many cases, the OOB radiation is even close to isotropic also when the in-band signal is highly directive. With the same total radiated power, the OOB radiation from large arrays is therefore never more severe than from a legacy system with the same adjacent-channel-leakage ratio. The OOB radiation is even less detrimental than from a legacy system since the high array gain of the in-band signal allows large arrays to radiate less total power than legacy systems. We also show how OOB radiation from large arrays varies with location in static propagation environments and how these effects vanish when averaged over the small-scale fading. A main conclusion is that the linearity requirement for large arrays can be relaxed as compared to legacy systems. Specifically, less stringent linearity requirements on each transmitter makes it possible to build large arrays from low-complexity hardware.

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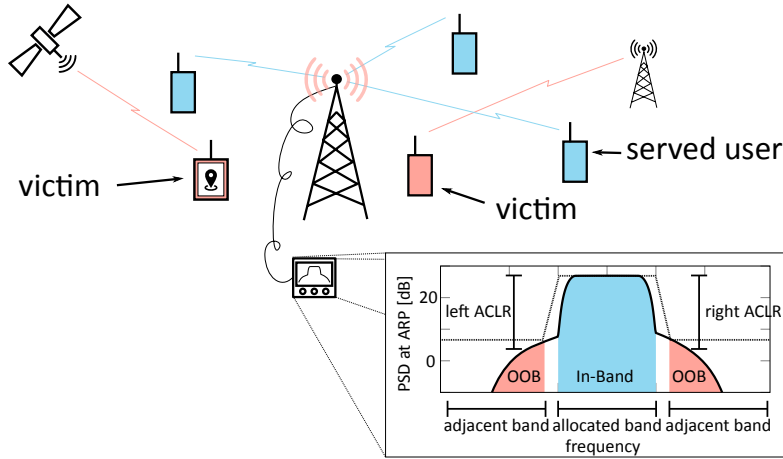


Figure 1: Victims of the OOB radiation from the studied base station are other wireless systems operating in the vicinity. To mitigate interference, hardware and their algorithms for signal compensation are calibrated based on conducted measurements of the ACLR at the antenna reference point. A zoomed in sketch of the power spectral density of the transmitted signal is shown at the bottom.

1 Background

Nonlinear hardware causes a radio system to emit spurious power outside its allocated frequency band. This *out-of-band* (OOB) radiation is illustrated in Figure 1, which shows the power spectral density of a typical transmit signal. The power outside the allocated band could harm the operation of a victim wireless system by interfering with its signal. Therefore, the amount of OOB radiation a base station is allowed to emit is regulated. Commonly, standards require that *conducted measurements*, i.e. measurements on the electric signal before the antenna at the *antenna reference point*, of the ACLR (Adjacent-Channel Leakage Ratio) be below a certain limit for each transmitter. The ACLR is the ratio between the power in the allocated band and the power in the adjacent band of the same bandwidth; if the powers in the two adjacent bands are different, the highest of the two is used. When there are multiple antennas, the ACLR is the ratio between the total in-band power (the sum over all antennas) and the total OOB power.

The *victim* of the OOB radiation can be a system with a completely different application and sensitivity from the studied system—e.g., radar stations, telescopes for space research, GNSS receivers, altimeters. A victim should be distinguished from *served users*, which are the receivers that operate within the allocated band and to whom the signal is intended. The scenario is depicted in Figure 1.

2 OOB Radiation from Large Arrays is Different

Two key 5G technologies—massive MIMO and millimeter wave (mmWave) communication—both use large arrays [1], which can be used to *beamform* a signal by letting each antenna in the array transmit precoded versions of that signal. When the precoding is done such that the signals add up constructively at the receiver, more power is received than if the signal was sent with the same total power from one of the antennas only. This *array gain* makes it possible for a large array to radiate a substantially lower amount of power than a legacy system and still serve its users with the same in-band power.

Unlike the OOB radiation from *legacy systems* [2, 3], i.e. SISO systems and small arrays, OOB radiation from large arrays has received little attention, [4, 5]. There are two main differences between the OOB radiation from a legacy system and from large arrays:

1. For legacy systems, OOB radiation has the same spatial characteristics as the in-band signal. For large arrays, where the signal envelope and thus the nonlinear distortion is different at each antenna, the OOB radiation can be beamformed differently from the in-band signal. When the array gain of the OOB radiation is small, the low radiated power from large arrays means that a victim receives less OOB power than from a legacy system with the same ACLR.
2. In legacy systems, with few radio chains and high output power, OOB radiation can be avoided by the use of high-end hardware or advanced compensation techniques, such as predistortion. The extra power required, e.g. by predistortion, to avoid OOB radiation is offset by allowing for the use of highly power efficient hardware. As the number of radio chains grows, cost, size and complexity of the hardware become impediments [6, 7]. Furthermore, the extra power that the compensation techniques consume grows proportionally to the number of radio chains. Their power consumption becomes so large compared to the small output power of the array that they no longer might be feasible. Large arrays are therefore likely to be built from low-complexity hardware that do not use advanced compensation techniques, which results in worse ACLR.

We will illustrate the spatial properties of the OOB radiation from large arrays in two types of propagation environments: a frequency-flat line-of-sight channel and a frequency-selective channel with isotropic scattering. Both static and mobile propagation environments will be considered; see Table 1. Measurements [8, 9] reveal that actual channels, many times, have both a line-of-sight component and dispersed components from scattering.

In line-of-sight communication, the time a mobile user equipment spends in one static lobe is relatively long. For example, with 100 antennas each separated by half a wavelength, the beamwidth is approximately 1.8° and a victim located 100 m from the base station and moving at 30 m/s perpendicular to the beam is inside the beam for

<u>static line-of-sight</u>	<u>mobile line-of-sight</u>
<ul style="list-style-type: none"> • beampattern is constant for long periods of time, both in static and mobile applications • outage rate/risk matters • beamforming of OOB radiation has to be considered 	
<u>static isotropic scattering</u>	<u>mobile isotropic scattering</u>
<ul style="list-style-type: none"> • coherence times is long compared to the sensitivity of the victims • outage rate/risk matters • the “beampattern” is static • beamforming of OOB radiation has to be considered 	<ul style="list-style-type: none"> • short coherence time • ergodic rate/performance matters • victims can code over many coherence times • OOB radiation “beampattern” changes rapidly • average OOB radiation has to be considered

Table 1: studied channels

100 ms. This could, for example, amount to an outage of 10^6 symbols, if the baudrate of the victim is 10 MHz. In the study of OOB radiation, we therefore model the line-of-sight channel as static, even if there is mobility.

In an environment with isotropic scattering, the victim only has to move half a wavelength to experience a different channel. The static and mobile scenarios therefore have to be studied separately. In static scenarios, the directivity of the OOB radiation might have to be considered. When either the served users are mobile or the victim is mobile, the amount of received OOB radiation will change rapidly. By coding over several coherence times for example, a victim can protect its operation from outage in individual coherence times. Therefore only the average OOB radiation is relevant in mobile scenarios.

3 Line-of-Sight Channels

Figure 2 illustrates how the in-band and OOB beampatterns from a large array differ. It also shows how they compare to an omnidirectional SISO system, whose ACLR is the same as that of the array, and whose transmit power is chosen such that all users receive the same in-band power. We see that there are bad directions, in which the OOB radiation is stronger, and that there can be good directions, in which there is very little OOB radiation.

Even though the figure shows multiuser cases with many equally strong beams, we note that spatially multiplexed users have hugely different path losses in many cases. To give the same quality of service to all users, the beams to different users have to have different powers. Often most of the radiated power will be directed towards the weakest user. This means that the single-user array with only one visible lobe is representative

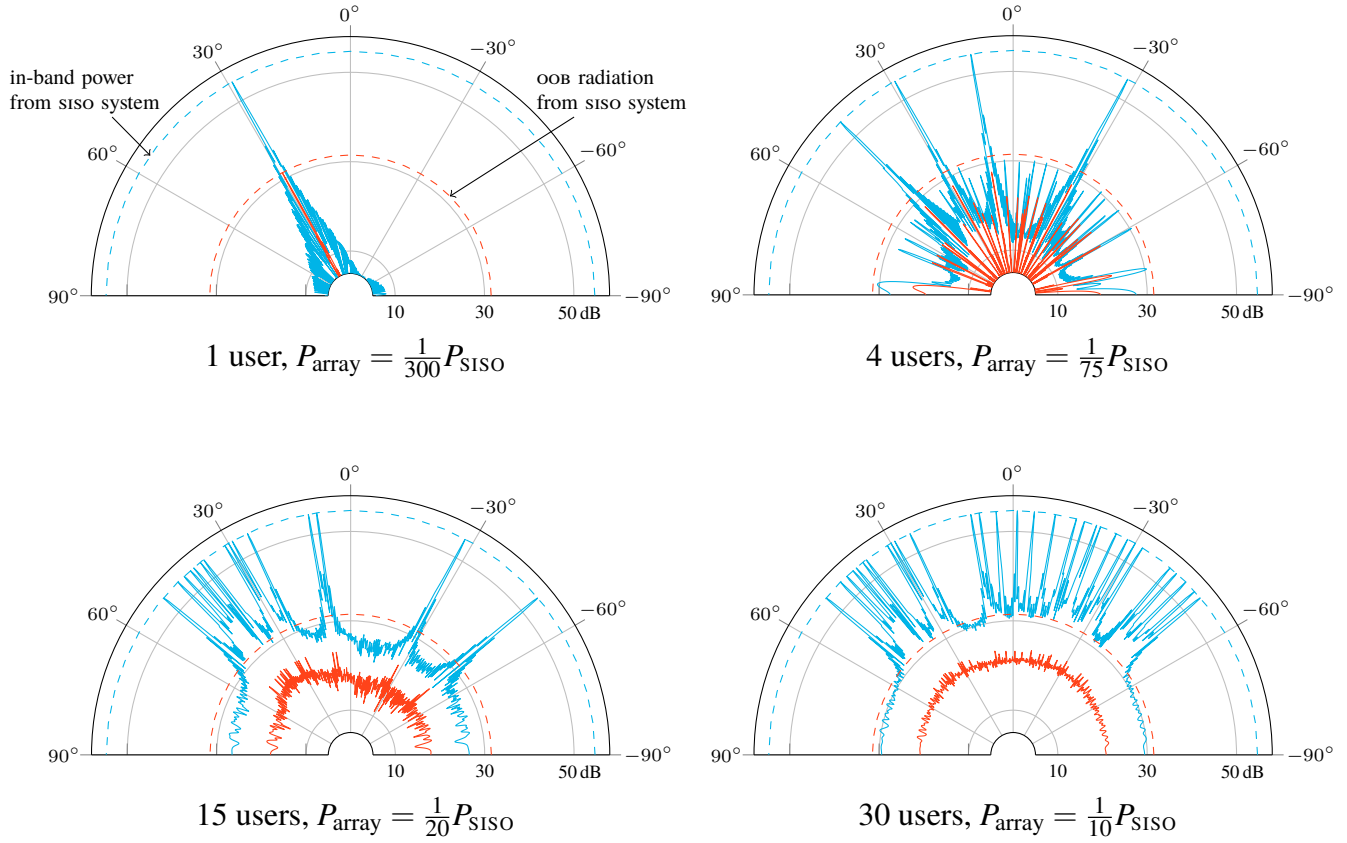


Figure 2: The radiated in-band (solid blue) and out-of-band power (solid red) from a large uniform-linear-array, which has 300 antennas with half a wavelength spacing, and which serves 1, 4, 15, 30 users. For comparison the radiated power from an isotropic SISO system with the same ACLR (23 dB) as the array is also shown (dashed lines). The transmitted power is scaled such that all users in the different systems receive the same power. Source code available [10].

also in many multi-user cases.

When the array serves one user, the OOB signal is beamformed in the same way as the in-band signal. There is therefore one direction, towards the served user, with as bad OOB radiation as from the SISO system. All other directions are very good—practically no OOB radiation is received in those directions. If the array serves multiple users, there are several bad directions. All of the bad directions are better than in the SISO system however, where the OOB radiation in any direction always is greater than or equal to the OOB radiation of the array in the worst direction. When the number of served users increases, the bad and good directions successively disappear; all directions become equally good and the OOB radiation is significantly lower than in the SISO system.

The array in Figure 2 is a linear array with uniform antenna spacing of half a

wavelength. It creates radiation patterns without significant grating lobes, except for the back lobe on the opposite side of the array. Other array geometries might introduce grating lobes however. Since the radiation pattern of the OOB radiation and the in-band signal are the same in the single-user case, grating lobes would cause the OOB radiation to also be radiated in the directions corresponding to those lobes. Since arrays with grating lobes in general also have narrower beams, the probability that a victim ends up in a beam of OOB radiation is not significantly changed by different array geometries. Furthermore, the OOB radiation in the directions of the grating lobes is still smaller than in the SISO system. The multiuser scenarios studied in Figure 2 have the same basic appearance for any array type.

It is important to note that the array has no directions with worse OOB radiation than the SISO system. Since the in-band signal is beamformed using the phase shifts that maximize its array gain, the OOB radiation can at most obtain the same array gain as the in-band signal, and therefore the OOB radiation is never stronger than in a SISO system with the same ACLR. The worst case, with a single served user, has one very specific direction, in which the OOB radiation is as bad as in the SISO system. All other directions are good.

There is a small risk that a victim stands in a bad direction, especially if few users are served. The worst case is when a system serves one user and a victim stands in the same direction as that user. In this case, the victim receives as much OOB radiation as from the SISO system. The probability that an unfortunate victim stands in a bad direction becomes smaller as the number of antennas grows large, and the main lobe becomes increasingly narrow.

Keeping the same ACLR requirements as in legacy systems would thus guarantee that no victim, not even the most unfortunate one, receives more OOB power than from a legacy system. The legacy ACLR requirement, however, can be relaxed if: (i) the array serves multiple users or (ii) one can allow for a certain probability that a victim is unfortunate and ends up in an OOB lobe.

4 Static Channels with Isotropic Fading

The received OOB radiation varies with the channel. If the channel changes slowly or if operation of the adjacent victim systems is sensitive to outage, e.g. when there is high reliability or latency requirements, the OOB radiation has to be constrained during every channel realization. Much of what was said in Section 3 about static line-of-sight channels carries over to slowly changing frequency-selective channels with isotropic fading. One difference, however, comes from the number of propagation paths, which is greater at lower frequencies.

A consequence of the multipath propagation of wideband signals is frequency-selective fading. The multiple taps of the channel make the OOB radiation less directive

in much the same way as serving more users did. Therefore, also when a single user is served by the array, the most unfortunate victim of OOB radiation still receives much less power than from a SISO system.

Another advantage of the large array as compared to the SISO system is channel hardening. Figure 3 shows the distribution of the received OOB power at a random victim for different systems with the same ACLR. It can be seen how constructive and destructive superposition, which is the result of multipath propagation, can result in large variations in OOB radiation in the SISO system. In a large array, however, channel hardening eliminates variations due to multipath propagation; variations only come from the directivity of the transmission. Just like in the line-of-sight system, the OOB radiation of the single-user system is slightly directive and there is a small risk that a victim will receive more OOB radiation than on average—in Figure 3, one victim in about a thousand receives 3 dB more OOB radiation than on average. The directivity becomes less prominent when the number of significant users, i.e. users to whom a significant part of the transmit power is directed, is increased. With ten equally significant users, the vertical slope in Figure 3 shows that the OOB radiation is practically isotropic. As mentioned in Section 3, however, large differences in path loss between the served users can mean that most of the radiated power is beamformed to a single user also in many multi-user cases. The single-user case is therefore representative also for many multi-user systems.

In Figure 4, a simple scattering environment is illustrated. Scattering centers have been randomly dropped over an area and a uniform linear array with 100 antennas beamforms to three users inside the area. It can be seen that the directivity, or the array gain, of both the in-band and the OOB signal varies with location. The variations, however, are much smaller for the OOB signal.

5 Mobile Channels with Isotropic Fading

An ACLR constraint only limits the average OOB power that a victim receives averaged over many channel fades and normalized by the path loss. This is enough when the coherence time is short and all gains can be averaged over the fading, because the victim can protect its operation from outage by error correcting codes for example. For large arrays, the same is true: a constraint on the transmitted OOB radiation limits the average OOB radiation received by the victim, if the channel to the victim is uncorrelated to the channels of the served users.

Since the total radiated power from a large array is lower than from a legacy system, the average received OOB power is also correspondingly lower when the two systems have the same ACLR, which was seen in Figure 3. The ACLR requirement should therefore be relaxed for the large array by an amount equal to the amount, by which the total radiated power is reduced, as compared to the legacy system. Since the in-band array gain grows

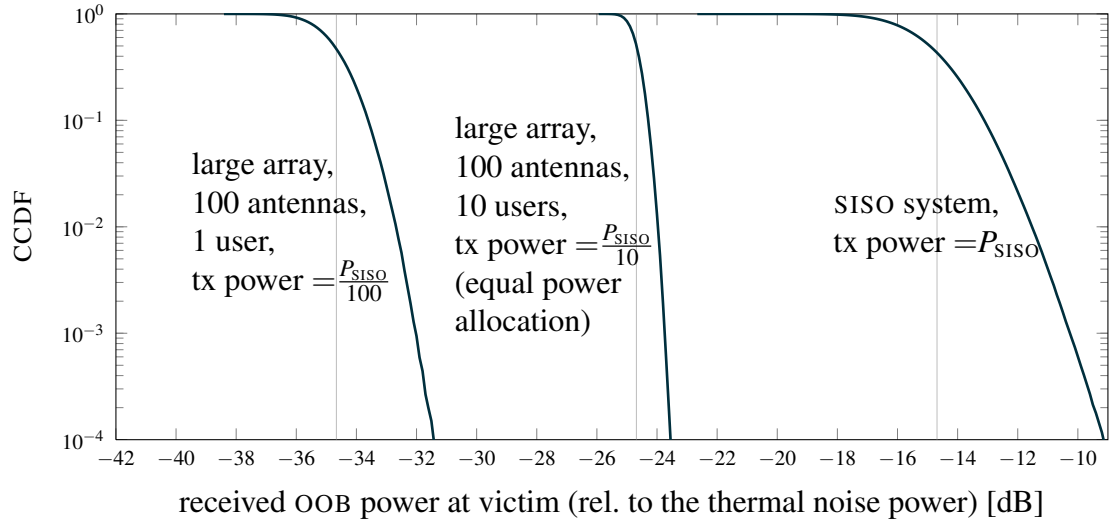


Figure 3: The distribution of the power received by a victim in the adjacent band in an IID Rayleigh fading propagation environment with a delay spread equal to 15 symbol periods. The radiated power is normalized such that the served users receive the same amount of in-band power (same signal-to-noise ratio) and the ACLR is the same in all cases. The transmitted signals to each of the ten users are assumed to be equally strong and, likewise, all path losses are equal. The mean received power is marked by vertical lines. Source code available [10].

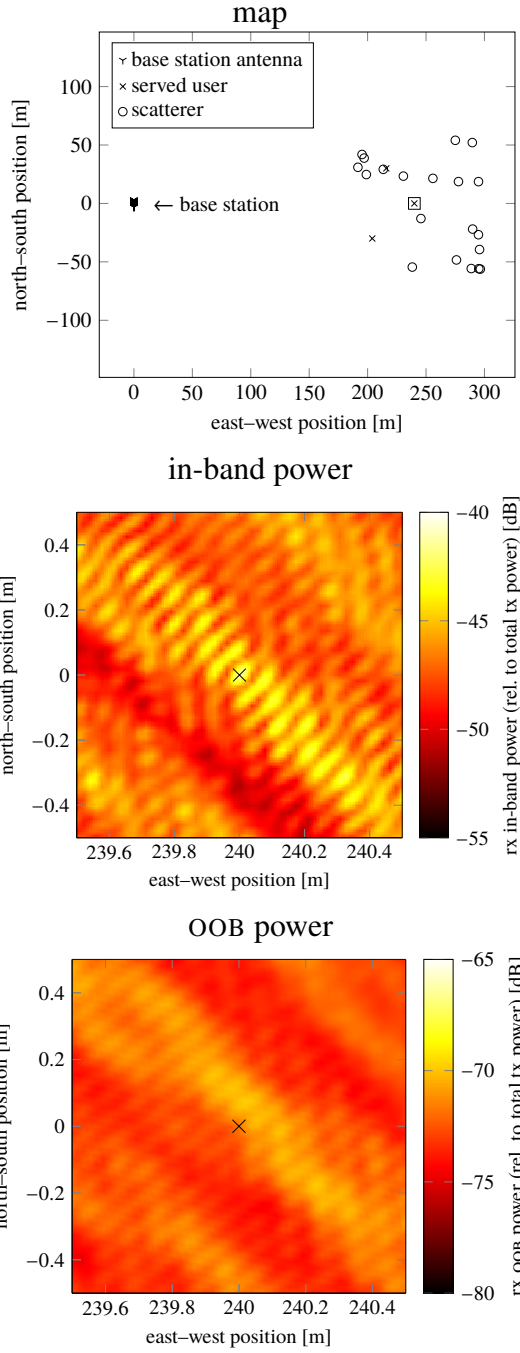


Figure 4: Heat map of in-band and OOB signal power intensity over the area marked \square in the uppermost figure, where the geometry of the setup can be seen. A linear uniform array with 100 antennas, half a wavelength apart, is located at the origin and 20 scatterers and three users are randomly placed in a 100 m large quadratic area 250 m east of the array. In 95 % of the locations, the power received in-band lies between -50 and -42 dB and OOB between -74 and -70 dB. Source code available [10].

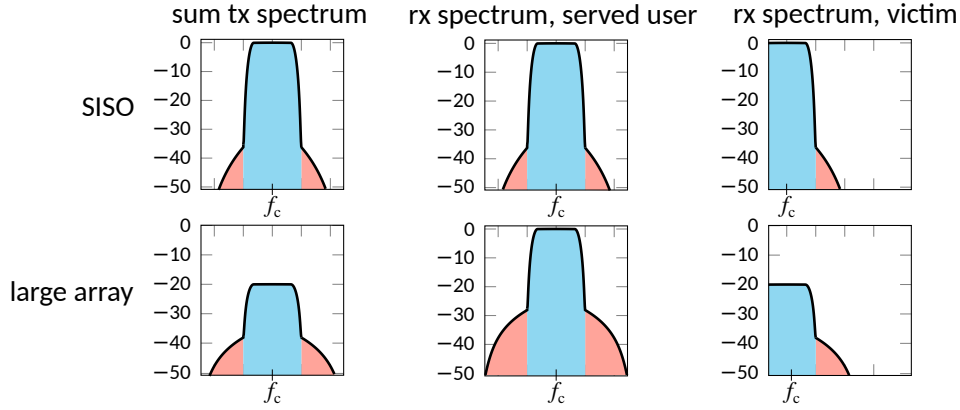


Figure 5: average power spectral densities (in dB relative to received power of the served user) in a SISO system and in a system with a large array

with the number of antennas of the array, the ACLR requirement can be relaxed more, the more antennas the array has. The radiated power, however, also increases with the number of served users and varies slightly depending on the employed beamforming technique. Therefore the ACLR requirement has to be specified in terms of these system parameters.

Figure 5 shows the average power spectral densities of two example scenarios; the path loss has been normalized for simplicity. In the legacy SISO case, highly linear hardware gives the transmitted signal a good ACLR. Consequently, the served user receives a sufficient amount of in-band power and, at the same time, the victim who operates in the adjacent band receives little disturbing power. In the large array case, the transmitted signal has an ACLR that is seemingly worse because less linear hardware is used; the transmitted power is also smaller. Because the signal is beamformed, however, the served user still receives a sufficient amount of in-band power. At the same time, the victim receives little disturbing power on average. This example illustrates that the ACLR constraint of SISO systems cannot directly be applied to arrays. The array gain of the in-band signal at the served users and the distribution of the OOB signal at the victim also have to be taken into account.

6 How to Measure OOB Radiation

To mitigate the disturbance of other systems, most communication standards, such as WCDMA, LTE, WiFi, and national regulatory bodies, such as FCC (the Federal Communications Commission) in the United States, limits the amount of permitted OOB radiation. This is usually done by enforcing a constraint on the ACLR of the signal and a maximum power level for the emitted OOB signal. For example, in LTE, the ACLR has to be better

than 45 dB or the absolute power spectral density of the signal in a wide outdoor area cannot exceed -13 dBm/MHz outside the allocated band, whichever is less stringent.

These regulations have been written with legacy systems in mind. The OOB radiation from a large array, however, is less problematic than from a legacy system and a relaxed ACLR constraint can therefore be used because large arrays radiate much less power than legacy systems both in-band and OOB. A more practical way to put the OOB constraint could be to regulate the total radiated power OOB instead of the relative ACLR, which we have seen does not necessarily correspond to how much OOB power that a victim is disturbed by. Neither for isotropic scattering nor for line-of-sight channels, should a constraint on the radiated OOB power increase linearly in the array gain of the in-band signal however. Since the array gain of the OOB signal, with high probability, is much smaller than that of the in-band signal, such a constraint would be much too strict.

In static scenarios, a constraint might have to include a safety margin to protect sensitive victims. The way to determine this safety margin, which depends on the propagation environment, the number of antennas and the number of served users, has to be carefully investigated. Because the OOB array gain is smaller than the in-band array gain, the OOB constraint is still relaxed compared to legacy systems however. For isotropic scattering, the safety margin can be read off from percentiles, like the one in Figure 3; it is many times small and can be neglected however. In a line-of-sight channel, this margin can be substantial and can be measured by the served users.

Some vendors and FCC [11, Sec. IV.G.3] have mentioned the possibility to measure OOB radiation “over the air”, i.e. to take measurements at selected positions around the transmitting array and draw conclusions about the received OOB power everywhere else from those measurements. The reason for employing such a strategy would be to avoid measuring directly on each of the individual transmit signals in the array and to make the constraint independent of the number of antennas and other system parameters. As long as the channel statistics of the measuring point is the same as that of the victim, the average measured OOB radiation will be the same as the signal power that disturbs the victim. When choosing the point of measurement, care has to be taken though. The channel to the measurement point cannot be correlated to the channel to the served users. Furthermore, in an environment that is largely static, a fixed measuring point will not see uncorrelated channel realizations, and thus not measure the average disturbance of a victim.

7 Conclusion: Implications for Standardization

We have showed that the OOB radiation that a victim will receive is significantly smaller from a large array than from a legacy system if the two systems have the same ACLR. This allows for relaxed ACLR constraints, which translates to laxer linearity constraints on the hardware. Furthermore, OOB radiation is close to isotropic in many cases, especially when

the number of users or the delay spread of the channel is large. This makes it redundant to measure the radiation pattern for each setup, which simplifies the measurement of OOB radiation.

As 5G is expected to incorporate large arrays, the behavior of OOB radiation needs to be properly taken into account when standards are developed. Regulatory bodies around the world are also looking into the possibility to free up the mmWave spectrum for cellular communication. Since mmWave communication will have to rely on large arrays to improve the link budget, a precise understanding of OOB radiation from arrays is important also to write proper regulations for the mmWave spectrum.

To set appropriate linearity requirements on the hardware is important, because it will be decisive for how future radio equipment will be designed. It will determine what amplifier architectures, digital-to-analog converters et c. that have to be employed. It will also influence what signal processing is required, such as predistortion, PAR reduction and low-PAR precoding. Power efficiency, system complexity, cost and size of future communication systems will all be affected by the way OOB radiation from large arrays is regulated.

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